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# ICT platforms in support of future railway systems

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**Abstract**

The predicted growth of transport, especially in European railway infrastructures, is expected to introduce a dramatic increase in freight and passenger services by the end of 2050. To support sustainable development of these infrastructures, novel data-driven Information and Communication (ICT) solutions are required. These will enable monitoring, analysis and exploitation of energy and asset information for the entire railway system including power grid, stations, rolling stock and infrastructure. To address these challenges, we propose a dynamically reconfigurable advanced communication platform enabling connectivity between a variety of monitoring devices and computational resources through a heterogeneous network infrastructure. The connectivity, coordination and collaboration required is provided, on an on-demand basis in accordance to the cloud computing paradigm. The benefits of this platform in the end-to-end service delay and power consumption are quantified over the 5G Bristol is Open network topology.

*Keywords:* Railway system, 5G network infrastructures,

**Nomenclature**

| | |
|---|---|
| ICT | Information Communication Technology |
| OCC | Operations and Control Centre |
| LTE | Long Term Evolution |
| SDN | Software Defined Network |
| ODM | Open Data Management |
| C-RAN | Cloud- Radio Access Network |
| NFV | Network Function Virtualization |
| VNF | Virtual Network Function |
| RH | Radio Heads |
| QoS | Quality of Service |
| DC | Data Center |

## 1. Introduction

Information and Communication Technology (ICT) platforms for future railway systems are expected to support a wide range of applications with highly variable performance attributes covering both operational and end-user service requirements. These platforms are expected to offer services ranging from delay sensitive video to infotainment services, and from best effort applications to ultra-reliable ones such as M2M (Machine-to-Machine) communications. An important consideration in the design of these platform is the very high mobility of train transportation systems beyond 2020 that in many cases may exceed 500 km/h. In addition to high mobility scenarios, connectivity for zero to low mobility cases (interconnecting devices at stations and substations) must be also supported. Other applications, such as remote maintenance of rolling stock and remote processing will have central role in future railway platforms [5G Vision].

In response to these challenges, we propose an advanced communication platform enabling connectivity between a variety of monitoring devices and computational resources through a heterogeneous network infrastructure. The connectivity, coordination and collaboration required is provided, on an on-demand basis in accordance to the cloud computing paradigm. To enable this opportunity there is a need for interconnecting ground infrastructures and on-board systems with the operations and control center (OCC), where the data centers (DCs) are hosted, through a heterogeneous network integrating wired and wireless network technologies. In this environment, optical network solutions can be deployed to interconnect distributed DCs, as they provide abundant capacity, long reach transmission capabilities, carrier-grade attributes and energy efficiency. At the same time, spectrum efficient wireless network technologies such as Long-Term Evolution (LTE) and WiFi can be effectively used to provide connectivity services to a large pool of mobile users and end-devices.

To address capacity limitations and high-speed mobility requirements of future railway systems, the communication platform will be managed through a flexible control plane offering the ability to create infrastructure slices over the heterogeneous network. Through this approach, railway system operators will be able to instantiate and operate several virtual infrastructures enabling multi-tenancy, supporting jointly energy and telecom services. This will allow operational and end-user services (e.g., Communications Based Train Control CBTC, Voice and data between central Command & Control and driver/cabin, streaming of surveillance video inside train and along railway infrastructure, monitoring of infrastructure devices, fleet management etc.,) currently provided through multiple technology-specific communication networks to be multiplexed over common infrastructures providing significant benefits in terms of cost and energy efficiency. The relevant benefits will be discussed and quantified using a purposely developed optimization tool.

## 2. Scenario Description and Key Technology Components

We consider a network infrastructure that relies on a set of optical and wireless network technologies to interconnect a variety of end-devices and compute resources. Through this approach, data obtained from various sources (monitoring devices, users and social media) can be dynamically and in real-time directed to the operations and control center (OCC) for processing.

The wireless domain of this infrastructure comprises cellular WiFi, LiFi and LTE technologies for the on-board and on-board to trackside communications (Fig. 1). These exhibit a high degree of heterogeneity [GSMA Intelligence] as they differ both in terms of operational and performance parameters, including spectrum use; antenna characteristics, physical layer encoding, sharing of the available spectrum by multiple users as well as maximum bit rate and reach. LTE is among the prime wireless access cellular technologies in 4G networks as it offers a theoretical net bit-rate capacity of up to 100 Mbps per macro-cell in the downlink and 50 Mbps per macro-cell in the uplink if a 20 MHz channel is used. These data rates can be further increased through Multiple-Input Multiple-Output (MIMO) technology. At the same time, LTE can provide improved Quality of Service (QoS) characteristics such as low packet transmission delays, fast and seamless handovers supporting high speed vehicular communications scenarios and operation with different bandwidth allocations.

Baseband signal processing functionalities in LTE systems are performed by the base band units (BBUs) that are either co-located with the antenna radio heads (RHs) or located remotely exploiting the concept of Cloud-RAN (C-RAN) [Tzanakaki, A., et al., 2016]. RHs are connected to the BBUs through high bandwidth links known as fronthaul (FH). C-RAN is expected to bring significant benefits in high mobility scenarios as it enables fast coordination and grouping of several cells forming super-cells with much larger size. To quantify the benefits of centralization in high mobility scenarios, let us consider the case where eNBs are placed 1.2 km apart. For a fast moving objects (i.e. trains) with a speed of 300km/h, handovers will be performed every 7s, leading to overutilization of network resources [CHINA mobile White paper], [Huawei]. However, by clustering several eNBs together handover frequency can be radically reduced.

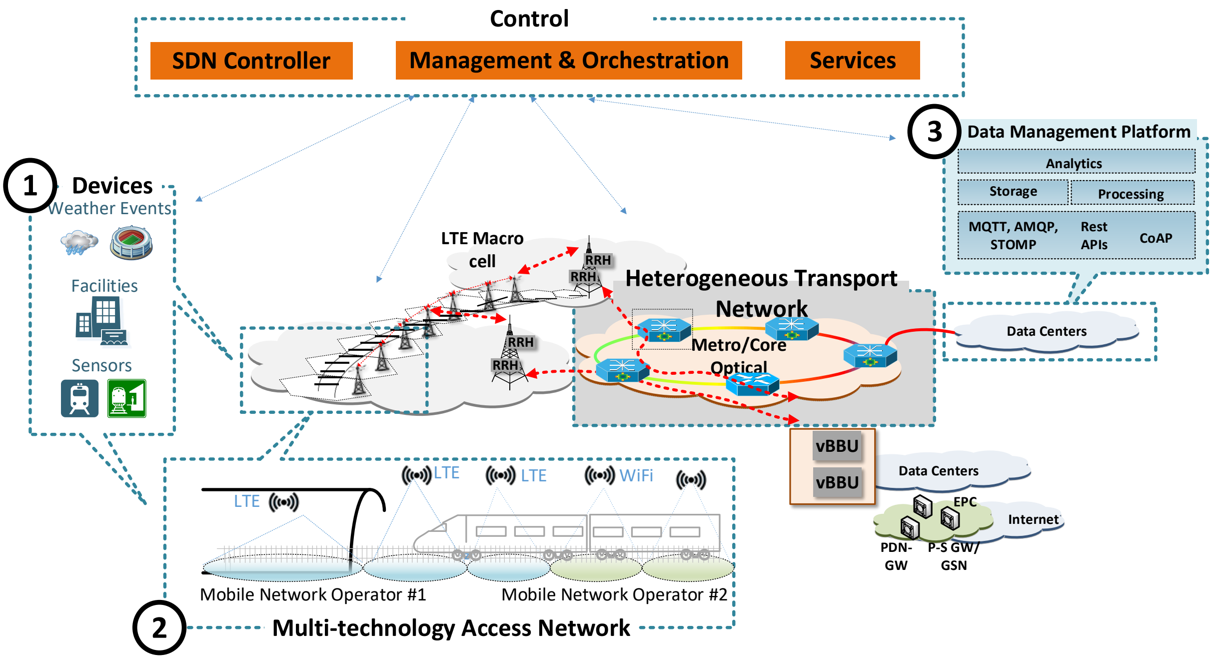


Fig. 1. Converged Heterogeneous Network and Compute Infrastructures supporting railway services: Use case where data are collected from various devices (1) are transmitted over a 5G network (2) to the cloud based data management platform (3).

To support the transport network requirements associated with C-RAN in railway environment, we propose the adoption of an optical transport solution offering high capacity and advanced features including dynamic bandwidth allocation both in the time and frequency domain [Tzanakaki 2013]. Given the technology heterogeneity of the proposed infrastructures, a critical function is interfacing between technology domains including isolation of flows, flexible scheduling schemes QoS differentiation mechanisms and mapping of different QoS classes across different domains. This can be achieved adopting flexible hardware functions that allow hardware repurposing through concepts such as hardware programmability. Hardware programmability can potentially enable dynamic and on demand sharing of resources guaranteeing also the required levels of isolation and security. In this context, programmable Network Interface Controllers that are commonly used to bridge different technology domains at the data plane can play a key role. These controllers have a unique ability to provide hardware level performance exploiting software flexibility and can offer not only network processing functions (i.e. packet transactions [Sivaraman 2016]), but also hardware support for a wide variety of communication protocols and mechanisms [Brebner 2015]. To enhance spectral efficiency, macro-cells can be complemented with small cells as they allow higher rates of frequency reuse over carefully designed geographical areas with easy access to the network backbone. In addition to small cells, given that WiFi networks are readily available in almost every public or private area and are easy to install and manage, significant benefits are expected by the joint consideration of WiFi and LTE systems. Additionally, the small cell concept can easily be extended to Visible Light Communications to overcome the high interference generated by the close reuse of radio frequency spectrum in heterogeneous networks. A network with multiple optical Access Points is referred to as an attocell network [Chen et al, 2016]. Since this operates in the visible light spectrum, the optical attocells do not interfere with any RF network. Therefore, the optical attocell layer adds data transmission capacity and enhances coverage while existing RF networks are not detrimentally affected.

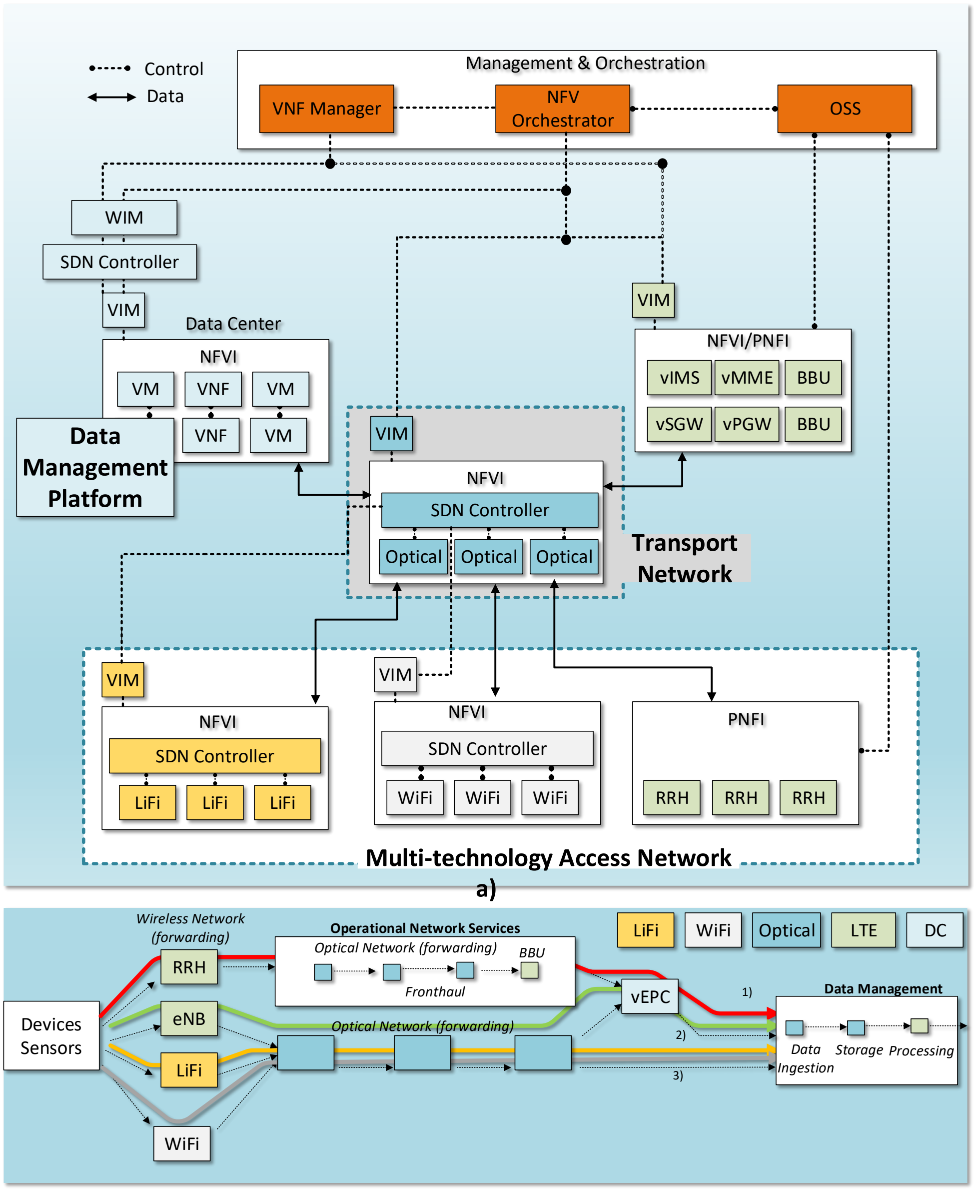


Figure 2. a) Example of an SDN/NFV-based control and management framework for Heterogeneous Network and Compute Infrastructures, b) Service chaining over heterogeneous network infrastructures supporting IoT services 1) IoT data stream over C-RAN, 2) IoT data stream over LTE, 3) IoT data stream over LiFi/WiFi.

## 3. Control and Management of the Integrated ICT Solution

As already discussed the proposed ICT platform (Fig. 1) exhibits a large degree of heterogeneity in terms of technologies. To address the challenge of managing and operating this type of complex heterogeneous infrastructure, we propose the integration of the Software Defined Networking (SDN) and Network Function Virtualization (NFV) approaches. In SDN, the control plane is decoupled from the data plane and is managed by a logically centralized controller that has a holistic view of the network [ETSI 2014]. In early SDN deployments the data plane implementations only supported packet forwarding related functionalities. However, the advent of new high performing technologies such as LiFi and dynamic optical railway network solutions necessitate the execution of much more complex networking functions such as scheduling, network monitoring and management, resource virtualization, isolation etc. In response to this, SDN controlled programmable hardware infrastructures can now effectively support implementation of these functionalities using high level programming languages. At the same time, NFV enables the execution of network functions on compute resources by leveraging software virtualization techniques [ETSI 2015]. Through joint SDN and NFV consideration, significant benefits can be achieved, associated with flexible, dynamic and efficient use of the infrastructure resources, simplification of the infrastructure and its management, increased scalability and sustainability as well as provisioning of orchestrated end-to-end services.

Examples of features that enable these benefits include the option to virtualize the separate control plane, using NFV and deploy Virtual Network Functions (VNFs). These are controlled by the SDN controller, to allow on demand resource allocation, able to support dynamically changing workloads [ETSI 2015]. SDN network elements can be treated as VNFs, since they can be implemented as software running on general-purpose platforms in virtualized environments. Both SDN and non-SDN models can be supported by SDN network elements. On the other hand, network applications can include SDN controller functions, or interact with SDN controllers and can themselves provide VNFs. Network elements controlled by SDN controllers can also provide Physical Network Functions (PNFs). Service Chaining (SC), combining and orchestrating physical and virtual network functions to support end-to-end service provisioning over heterogeneous environments, is considered to be one possible network application.

A typical example of an SDN /NFV architectural framework is illustrated in Fig. 2 a). It is observed that network function virtualization infrastructures (NFVI) comprising LiFi and WiFi components together with traditional non-virtualized physical infrastructures (e.g. LTE deploying RRHs) are inter-connected with the pool of computing resources, through SDN based optical network domains. Each WiFi/LiFi administration domain may host multiple SDN data plane elements and expose its own virtualised resources through an SDN controller to the upper layer SDN controllers. In our case the upper layer as illustrated in Fig 2 (a) refers to the optical layer. The hierarchical SDN controller approach adopted can assist in improving network performance and scalability as well as limit reliability issues [ETSI 2015]. In the proposed architecture, the top network controller will manage network resource abstractions exposed by the lower level controllers that are responsible to manage the associated network elements. Orchestration of both computation resources necessary to support the IoT use case and network resources is performed by the NFV Orchestrator and can be used for the support of multi-tenant chains, facilitating virtual infrastructure provider operational models. It is also responsible to interact with third party or legacy resources and support systems (OSS).

## 4. Modeling and Optimization

To address the great diversity of requirements introduced by the upcoming services in a cost-effective and energy efficient manner, optimal resource assignment considering the unique application and device characteristics is needed. In achieving this goal, the development of intelligent optimization algorithms considering different Key Performance Indicators (i.e. capacity, latency, energy consumption) for all physical and virtual network providers can play a key role. In the SDN/NFV architecture shown in Fig. 2, this process is located at the management and orchestration layer, offering to network service providers suitable tools that can assist in performing a broad range of tasks, including [ETSI 2015]:

- activities related to service chain management, able to Create/Delete/Update network SCs and a set of other relevant network functions

- management of SCs considering virtual and/or physical resources and definition of traffic rules to dictate the selection of the optimal chain out of a set of possible chains
- scale-in/out functionalities such as the, ability to bring up/down multiple network functions on an on-demand basis
- traffic offloading from one forwarding entity to another
- unified orchestration of compute and network elements
- service orchestration with legacy or third party Operation Support System (OSS)

The combination of these tools facilitates the support of any mix of services, use cases and applications and can assist in addressing both technical and business challenges anticipated to arise in future network infrastructures. A specific use case that can be used to highlight the role of these tools is the provisioning IoT Services in railway environments, deploying a heterogeneous network infrastructure. Though this approach, scalability issues raised in the current railway OCC systems can be addressed by offloading intensive tasks (or accessing hosted content) to data management platforms hosted in the cloud.

To provide cloud-based IoT services, the orchestrator instantiates different type of VNFs that are deployed and chained together, each having specific processing and bandwidth requirements. Based on the type of wireless access technology (i.e., RRH, eNB, WiFi, LiFi) used to forward data from sensing devices (End-Point A in Figure 2 b)) to the optical transport and the DCs where the Open Data Management (ODM) platform is hosted, multiple candidate service chains can be created. To realize each SC, sufficient network bandwidth and processing capacity must be allocated, corresponding to specific physical resources, for the interconnection and deployment of VNFs. VNFs are then processed in the order defined by the corresponding SC. For example, SC1 in Fig. 2(b) illustrates the case of traffic forwarding to remote DCs over the RRHs. To realize this, wireless signals received by the RRHs are forwarded over an optical transport network to the BBU pool and then to the DC location. Flow conservation as well as mapping and aggregation/de-aggregation of traffic between different domains should be also satisfied.

Apart from network and capacity constraints, end-to-end delay is an important Key Performance Indicator that needs to be also considered in the analysis. In highly loaded heterogeneous networks, end-to-end delay can be greatly influenced by queuing delays associated with the interfaces. Therefore, applying specific queuing policies and scheduling strategies at these locations is very important. Significant delay benefits can be achieved by instantiating the necessary network functions and reserving the required virtual/physical resources. End-to-end delay can be mathematically modelled through queuing models and the adoption of closed form approximations derived by modeling the different network domains as open, closed and/or mixed queuing networks. An example is illustrated in Figure 3 (c) where a three-dimensional Markov chain is adopted to model the three wireless access technology domains i.e. LTE, LiFi and WiFi. Each dimension of the Markov chains corresponds to a different virtualized wireless access domain with its state space defined as $\mathcal{S} = \{(i,j,k) | i \leq \mathcal{I}, j \leq \mathcal{J}, k \leq \mathcal{K}\}$, where $i, j$ and $k$ correspond to the virtualized resources used across the LTE, LiFi and WiFi dimension respectively and $(i,j,k)$ is a feasible state in $\mathcal{S}$. Note that $\mathcal{I}$, $\mathcal{J}$ and $\mathcal{K}$ correspond to the maximum set of resources that can be allocated to a specific provider. A key characteristic of the proposed scheme is that it allows modeling of traffic offloading decisions from one entity to another (i.e. LiFi to WiFi or LTE) as well as modeling of the arrival of a new service request by modifying the corresponding state i.e. $(i,j,k) \rightarrow (i+1,j,k)$ when a new forwarding decision is applied through the LTE network. The steady state probabilities of the Markov process can be determined in a unique way using the well-known matrix-geometric solution techniques and the corresponding service delay can be determined.

Markov chain models can be effectively used to evaluate the performance of domains where statistical independence between arrivals and services exists. Therefore, they can be applied to describe scenarios where virtual resources are realized through isolated physical resources such as different channels, spectrum, wavelengths etc. However, these models cannot be extended to technology domains where common buffers are shared among multiple virtual flows. A typical example for this exception applies to the edge nodes of the optical domain where common FIFO queues can be traversed by several virtual flows. A solution to this problem is to adopt the concept of virtual output queues (VOQ) that can achieve traffic isolation among flows, providing at the same time flow-level bandwidth provisioning with strict delay guarantees (see Figure 2 c)) [Jin 2013]. It should be noted that VOQ do not refer to physical entities, but correspond to pointers pointing to specific packets of the physical queues. In practice, they can be implemented in programmable hardware through the development of appropriate flow scheduling algorithms whereas centralized control can be implemented in Openflow.

## 5. Mobility considerations

An additional consideration to be taken into account during the operation of this type of infrastructures is train mobility. To handle mobility, redundant physical resources should be reserved to support uninterrupted service chaining. The amount of redundant resources increases with the speed of end-user mobility, the size of the wireless cells (mobile users associated with small cells will exhibit very frequent handovers) and the traffic model adopted. Based on their technical characteristics, the wireless access technologies adopted in this work, can address end-user mobility with different levels of effectiveness. E.g. LiFi providing high capacity levels is most suitable for indoor environments with limited end-user mobility, whereas WiFi and LTE can support lower capacities but higher mobility levels, with LTE being the most suitable technology for high speed vehicular communications. To maximize the benefits provided by the available technologies users with low mobility are offloaded to the LiFi domain releasing WiFi and LTE resources for mobile users. It is clear that, seamless handovers for a mobile user can be 100% guaranteed only if the required amount of resources is reserved for all its neighboring cells. However, to limit overprovisioning of resources, a more practical approach is to relate the reserved resources in the neighboring cells with the handover probabilities across LiFi and LTE cells and reserve a specific set of resources for handover purposes.

Similarly to the static cases described above, a five-dimensional Markov chain can be adopted to evaluate the performance of the virtualized wireless access network under mobility where two additional dimensions have been introduced to model handovers across WiFi and LTE. Given that users are much more sensitive to call dropping than call blocking a percentage of the virtualized resources is reserved for handovers. Thus, new service requests can use resources up to a specific threshold above which new requests are dropped. On the other hand, mobile users are dropped when all resources are already in use. In this case also, a closed form approximation of the systems' state probabilities can be extracted using dimensional reduction techniques. The redundant resource requirement imposed for mobility purposes propagates also from the wireless access domain to the optical network and compute domains as depicted in Figure 3 c).

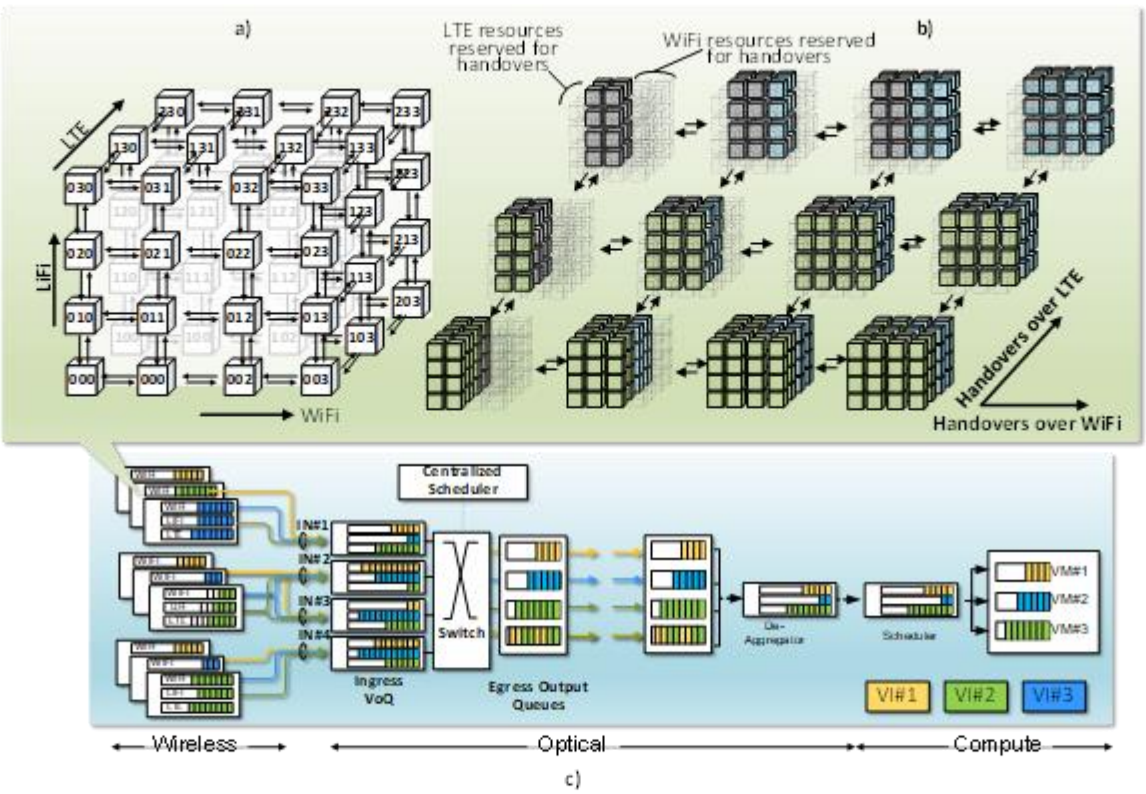


Figure 3. Modeling queuing delays in converged network environments a) three-dimensional Markov chain for estimating delays in virtualized wireless access network with traffic offloading capabilities from one forwarding entity to another b) five-dimensional Markov chain modeling mobility, c) End-to-end model as a network of queues. .

Taking into account the above considerations, a multi-objective optimization problem can be formulated that optimizes the performance of the converged network and computation infrastructure considering also the battery lifetime of the sensing devices under delay and mobility constraints. The description of a similar multi-objective optimization framework can be found in [Tzanakaki et al 2015].
The output of this optimization problem can drive the selection of the optimal SC out of set of multiple chains. In addition, it can identify possible locations where VNFs or PNFs can be placed as well as the optimal wireless access technology that should be used.

## 6. Performance Evaluation

### *6.1. Simulation Environment and Parameters*

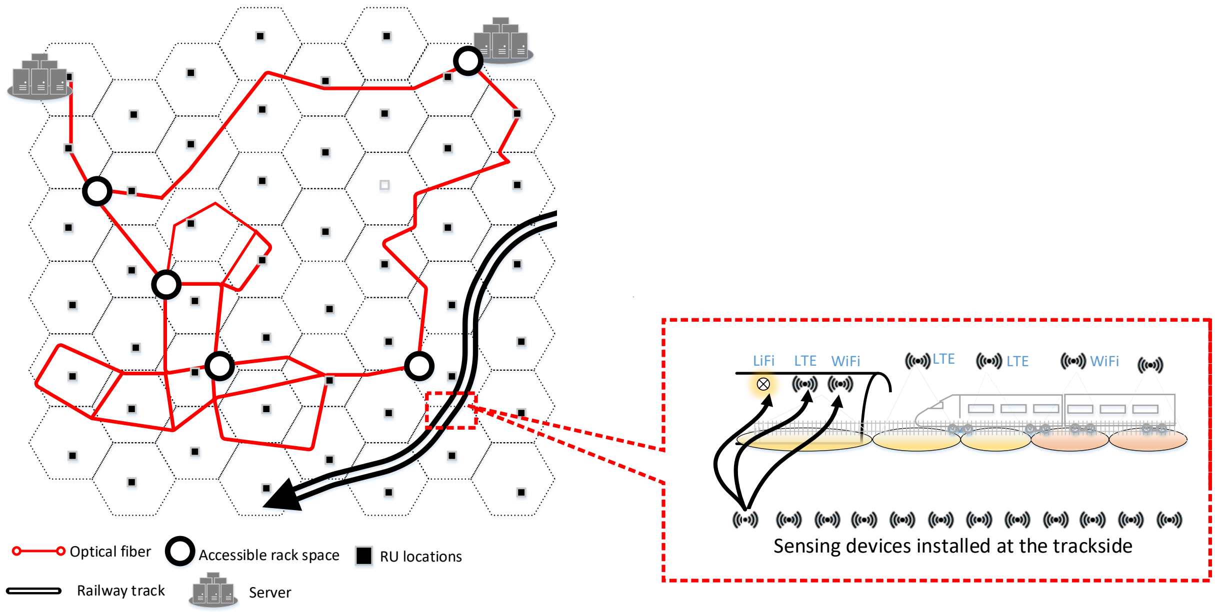


Figure 4. Bristol is Open Network Topology.

The proposed framework is evaluated using the infrastructure topology, illustrated in Figure 4. This infrastructure covers a 10x10 km2 area over which 50 RRH units are uniformly distributed and comprises a set of optical edge nodes in the optical segment, and optical point-to-point links for fronthauling the RRHs. The optical network technology adopted deploys a single fiber per link, 4 wavelengths per fibre, wavelength channels of 10 Gbps each, minimum bandwidth granularity of 100 Mbps and maximum link capacity of 40 Gbps. The power consumption model for the optical nodes is provided in [Tzanakaki 2013]. Furthermore, a 2×2 MIMO transmission with adaptive rank 10 MHz bandwidth adjustment has been considered, while background network traffic over the serviced area according to real datasets reported in [Chen X. 2015].

The railway-related network traffic is generated by a set of sensing devices installed both on-board and at the trackside. This traffic needs to be transferred at the servers where the ODM platform is located and processed by a specific set of computing resources. The power consumption of each device when information is transmitted over the LTE is 0.3W and 1.3W under idle and transmission/reception mode, respectively. The whole area is also covered by a set of WiFi access points offering 135 Mbps capacity having power consumption 1.28 W during data transmission, 0.94 W during data reception, 0.82 W under idle mode and 64 mW under sleep mode. In addition to this, a set of LiFi access points providing indoor coverage offering 300 Mbps data rate with 0.66 W power consumption under 200 lx light intensity is considered. Finally, each DC has a processing capacity of 80 Giga IPS and its power consumption follows the step-size power consumption model [Tzanakaki 2015]. The objective of the optimization framework is to identify the optimal SCs in order to jointly optimize the performance of converged network and computation infrastructure as well as the battery lifetime of the sensing devices. The former can be achieved by identifying the optimal routing paths and the location of the DCs where demands need to be processed, whereas the latter by ensuring that all sensing devices will forward their traffic through the optimal wireless access network technology. Through the appropriate selection of the optimal wireless access technology (WiFi, LiFi, LTE), sensing devices will try to prolong their battery lifetime without violating QoS specifications.

Figures 5-6 illustrate the impact of service requirements in terms of network traffic and mobility on the end-to-end service delay and the average power consumption per sensing device.

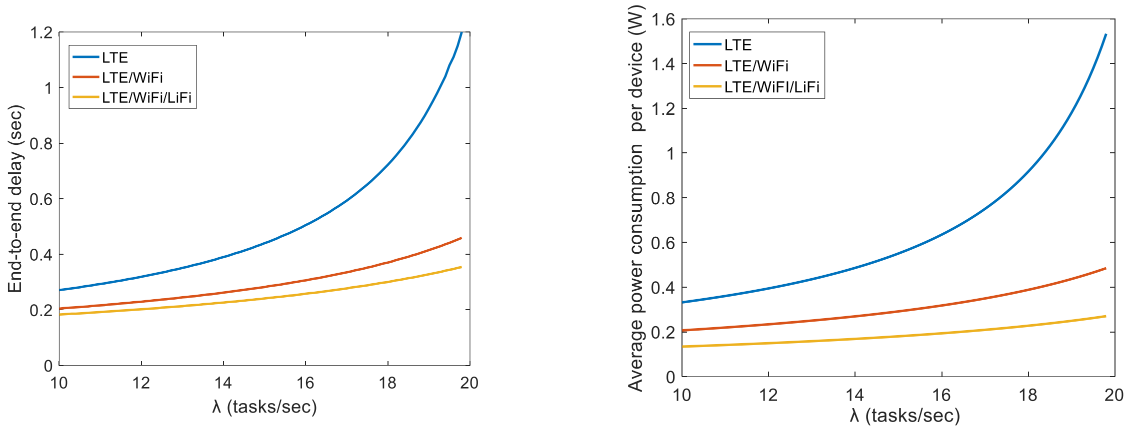


Figure 5. Impact of network integration on end-to-end service delay and sensing device power consumption (compute-to-network ratio= 0.03)

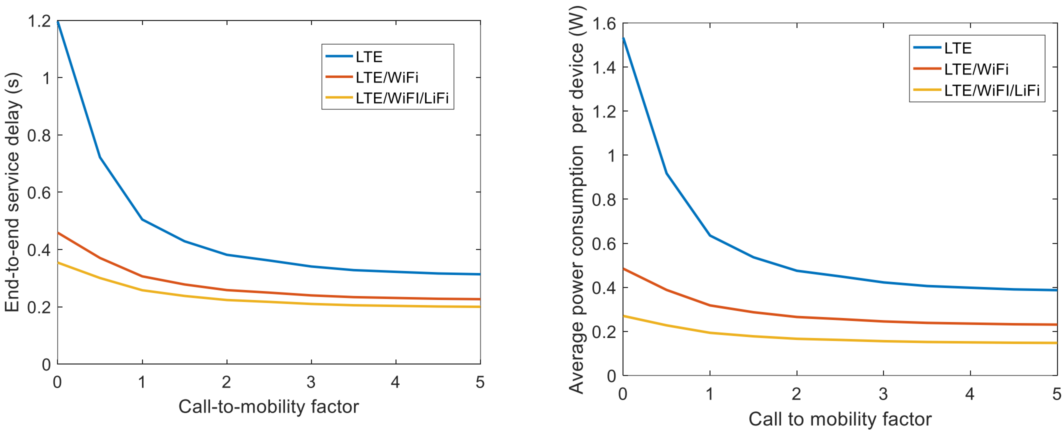


Figure 6. Impact of mobility on end-to-end service delay and device power consumption for Wireless Access Technologies (λ=10)

To achieve this, the Network-to-compute resources and the Call-to-mobility [Fang 2002] ratios are introduced to capture the communication cost and the average speed of the sensing devices, respectively. The former is used to capture the relation between computational and network bandwidth requirements, while the latter is defined as the fraction of the service holding time over the cell residence time. From Figure 5 it is observed that with the increase of the network load both the end-to-end service delay and the power consumption of the mobile devices is increased. However, for higher degree of network convergence we are able to drastically reduce the service delay and the power consumed by the mobile devices.

As also discussed in [Tzanakaki 2013], when mobility is high (lower call-to-mobility factor), additional resources are required to support the seamless handovers in the wireless access domain. This additional resource requirement also propagates in the optical railway network and the DC domain in order to ensure availability of resources in all domains involved (wireless access and backhauling, optical railway network, and DCs) to support the requested services and enable effectively seamless and transparent end-to-end connectivity between sensors and the computing resources. This leads to underutilization of network resources and therefore increased delays. The present approach, through the higher degree of consolidation and the better utilization of the network resources it offers, can handle high degrees of mobility and also support services with significant communication requirements in a very efficient manner (Fig. 6).

## 7. Conclusion

This paper presents a next generation ubiquitous converged infrastructure integrating an advanced optical railway network solution offering sub-wavelength switching granularity with a hybrid wireless access network based on LTE, WiFi and LiFi technologies. An architectural framework inspired by the ETSI NFV/SDN reference model enables control and management of this highly heterogeneous environment and facilitates end-to-end service orchestration with guaranteed Quality of Service. Numerical results indicate that through tight integration of all networks, traditional technology barriers that prevent the deployment of cloud computing services in railway environments can be alleviated leading to significant improvements in terms of throughput, data density and energy efficiency.

## Acknowledgement

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